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NOMENCLATURE

List of Abbreviations

CC	charge controller
DoD	depth of discharge
PR	performance ratio
SOC	state of charge
ToU	time-of-use

1 SUMMARY

As in the previous two reports, we present the results in two parts related to demand-side storage modeling and grid modeling. In Milestone report 2 we developed a multi-period mixed-integer linear program (MILP) with the objective of maximizing the economic benefits for a single user. The model is capable to identify the feasibility of investment in PV and/or battery systems. When feasible, it can find the best PV and/or battery systems from the mix of available options. This decision support program enables the consumer (spanning from a small house to large-scale industrial plants) to implement the most efficient electricity management strategy while achieving the goal of a minimum electricity bill. In this Milestone 3 report, we have extended the model to feeder level with aggregation of multiple houses which will be discussed in Chapter 2.

For reference, the Milestone 3 details are as follows:

- Modelling framework based on the legacy grid and the widest possibilities for new sources of energy, storage and loads
- Progress on development of security scanning tools and framework - which can check balancing, constraints, dynamics, stability, vulnerability according to indicators of performance for large networks with renewables and new loads
- Mid term progress report, including linking between P1 and P2, P3 and P4

Furthermore, in Milestone 2 we also reported our progress on formulation of methodology and preliminary grid modeling framework. More specifically, the performance of the simplified Australian power grid (the 14-generator Adelaide model) is analyzed in detail considering integrating renewable energy sources (RES) with different penetration levels. DIgSILENT is used to make steady state stability analysis. Continuing this previous work, we developed more comprehensive scanning tools and a framework for security assessment

according to Milestone 3. This work is aimed to produce a novel screening tool for the stability of large numbers of scenarios of renewable power placement.

In parallel with this work, postgraduate students are studying some key developments on: 1) use of aggregate modeling of the demand-side in stability studies (as was introduced in the Milestone 1b Report); 2) stability sensitivity to renewable power type and placement, specifically wind farms and concentrated solar thermal with storage and HVDC; 3) modal interactions between renewable power frequencies and system dynamics ;and 4) vulnerability analysis as integration of renewable power increases. Results in these projects are not explicitly within the scope of work funded by CSIRO, but can inform the project and will be reported in summary form in due course.

Finally, a mid-term progress report is included.

2 SCALE-UP OF STORAGE MODEL TO FEEDER POINT

In this Section, the recent progress on modelling with storage will be described. The mid-term progress report of both parts of the project is given in Section 4.

2.1 Feeder with distributed PV and battery

In Milestone reports 1b and 2 we discussed the necessity of increasing the granularity of energy storage in this future grid study. Prior studies, including the Future Grid Forum, excluded the distribution network (generation and storage) from their model and used an aggregated model for demand affected by storage at state (transmission) level. In this study, storage is allowed at all locations in the grid including transmission, distribution, and demand side. We are aiming to granulate the model further to city level where weather and demographic areas can be more uniform.

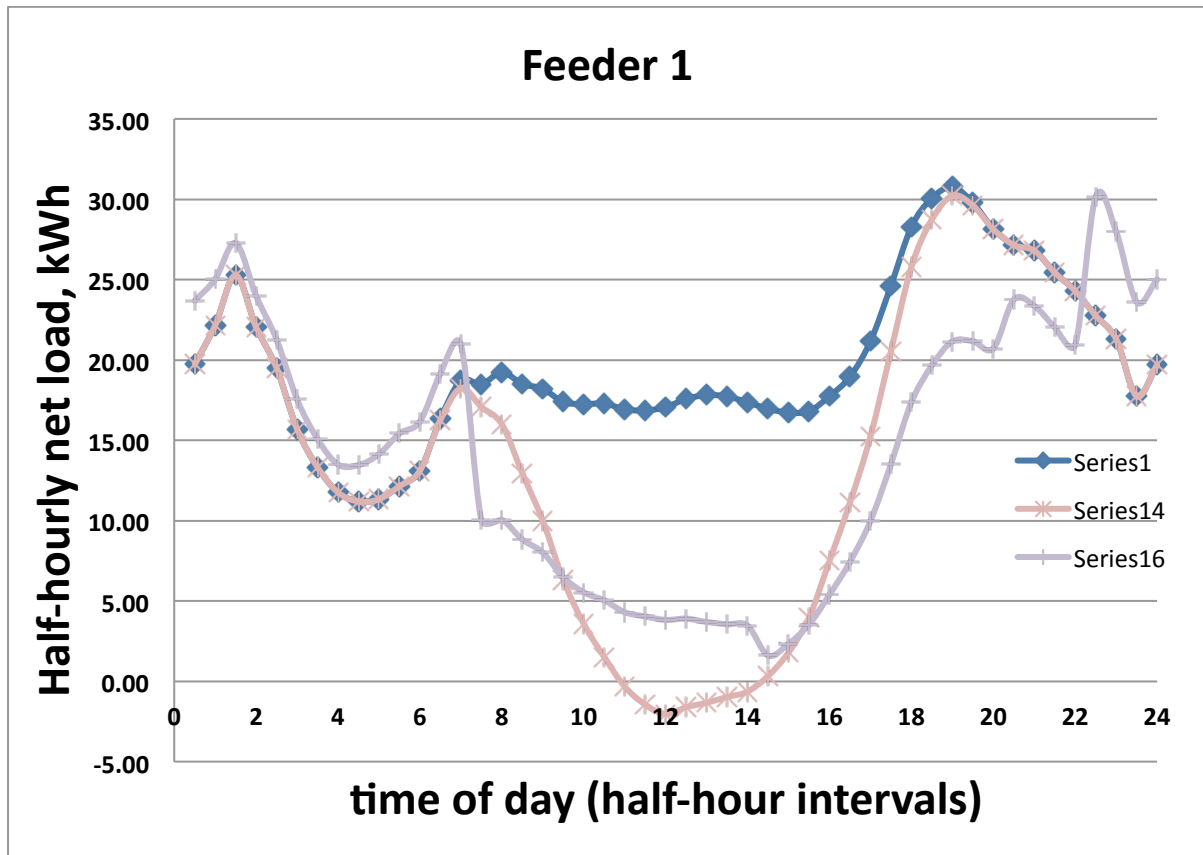
At Milestone 2, we described a multi-period mixed-integer linear program (MILP) with the objective of maximizing the economic benefits for a single user. The model is capable of identifying whether it is economical to invest in PV and/or battery systems. If it decides in favour of the application of PV-battery systems, it can find the best system configuration from the mix of available options. Here we extend the model to feeder level with aggregation of multiple houses. Given the PV and/or battery size of every home along a feeder, the model finds the optimal operation schedule of each home from which its net load is identified. With aggregation of all homes along the feeder, the net load profile at the feeder point is identified. Our study is based on real load data provided by Ausgrid for 300 homes in Sydney [1]. We developed models for six feeders each with 50 homes. Each home operates its own PV and battery, when available. The method of operation is based on the MILP model that we introduced in Milestone report 2. The current electricity price consists of three ToU tariffs (off-peak = 0.13 A\$/kWh, shoulder = 0.21 A\$/kWh, and on-peak = 0.53 A\$/kWh). Given these ToU electricity prices, each house desires to minimize its electricity bill over the year. In this study batteries are lithium-ion with a charge/discharge rate of two hours and DoD of 85%. The charge controllers and inverters have efficiency of 98% each way. The electricity FiT is 8.0 c/kWh during the base year.

The key issue in any futuristic study is the projection of parameters. For instance, the uptake of PV and storage at the demand-side is subject to considerable uncertainty. Here, we develop 16 different PV-battery uptake scenarios starting with extreme scenario 1, considering zero PV uptake and zero battery uptake, and ending with Scenario 16, with 100% PV uptake and 100% battery uptake.

The scenarios also assume different battery uptake for consumers with and without PV installation. A schematic of these 16 scenarios is given in Figure 2-1. The summary of scenarios and the total PV and battery uptake for feeder 1 is given in Table 2-1.

4	20	50	20	21	45
5	50	0	0	49	0
6	50	20	5	49	14
7	50	50	20	49	50
8	50	70	50	49	87
9	70	0	0	62	0
10	70	20	5	62	27
11	70	50	20	62	69
12	70	70	50	62	89
13	70	100	70	62	118
14	100	0	-	83	0
15	100	50	-	83	77
16	100	100	-	83	127

Figure 2-2 also illustrates one of the critical grid operation challenges that might follow for extensive PV uptake at demand-side. The challenge is the sharp drop and rise in the load profile (Scenario 14) during mornings and afternoons, respectively. This steep load change, if it happens, will require some large scale generators to notably ramp down (morning) or ramp up (afternoon) in a couple of hours. This might pose a serious challenge to the grid, due to flexibility limitations of some conventional generators, as well as the network which was not planned to accommodate these power flows. Figure 2-2 also illustrates the annual average net load of the scenario 16 which assumes all 50 homes along the feeder have installed both PV (83 kW) and battery storage (127 kWh).



Scenario	PV uptake (%)	Battery uptake (% homes w PV)	Battery uptake (% homes w/o PV)
1	0	0	0
14	100	0	0
16	100	100	-

Figure 2-2: Annual average net load of feeder 1 for scenarios 1, 14 and 16.

In scenario 16, the feeder’s load increases during offpeak periods (before 7 am and after 10 pm) as a result of batteries being charged to use their energy at a later time during the day. It is evident that during the shoulder time of 7-9:30 am (when homes along the feeder experience a morning peak, and solar irradiation has yet to peak), the net load of scenario 16 becomes lower than scenario 14. This implies that the batteries of the homes decide to use part of their storage within this period. After 9:30 am and till 2 pm (i.e. beginning of peak ToU hours), the net load profile for scenario 16 moves above that for scenario 14 and stays positive. This is while scenario 14 had a negative net load for a few hours (solar irradiation

peak) within this period. This is because batteries along the feeder, at scenario 16, are charged, during this time, to their full state to use the charge later during peak ToU periods. This allows the homes to store their low value PV output (with FiT of 8 c/kWh) and utilize it when the grid ToU electricity price is 53 c/kWh. This is evident from Figure 2-2 for the periods during 2-8 pm (peak ToU) within which the net load profile for scenario 16 is lower than that for scenario 14. This trend is reversed from 10 pm onwards when off-peak times start and batteries initiate their recharge process.

The net load profiles of all 16 scenarios are illustrated in Figure 2-3. It is evident that as the percentage of homes with PV and battery increases the gap between the scenarios and the base-case scenario (Scenario 1) also increases.

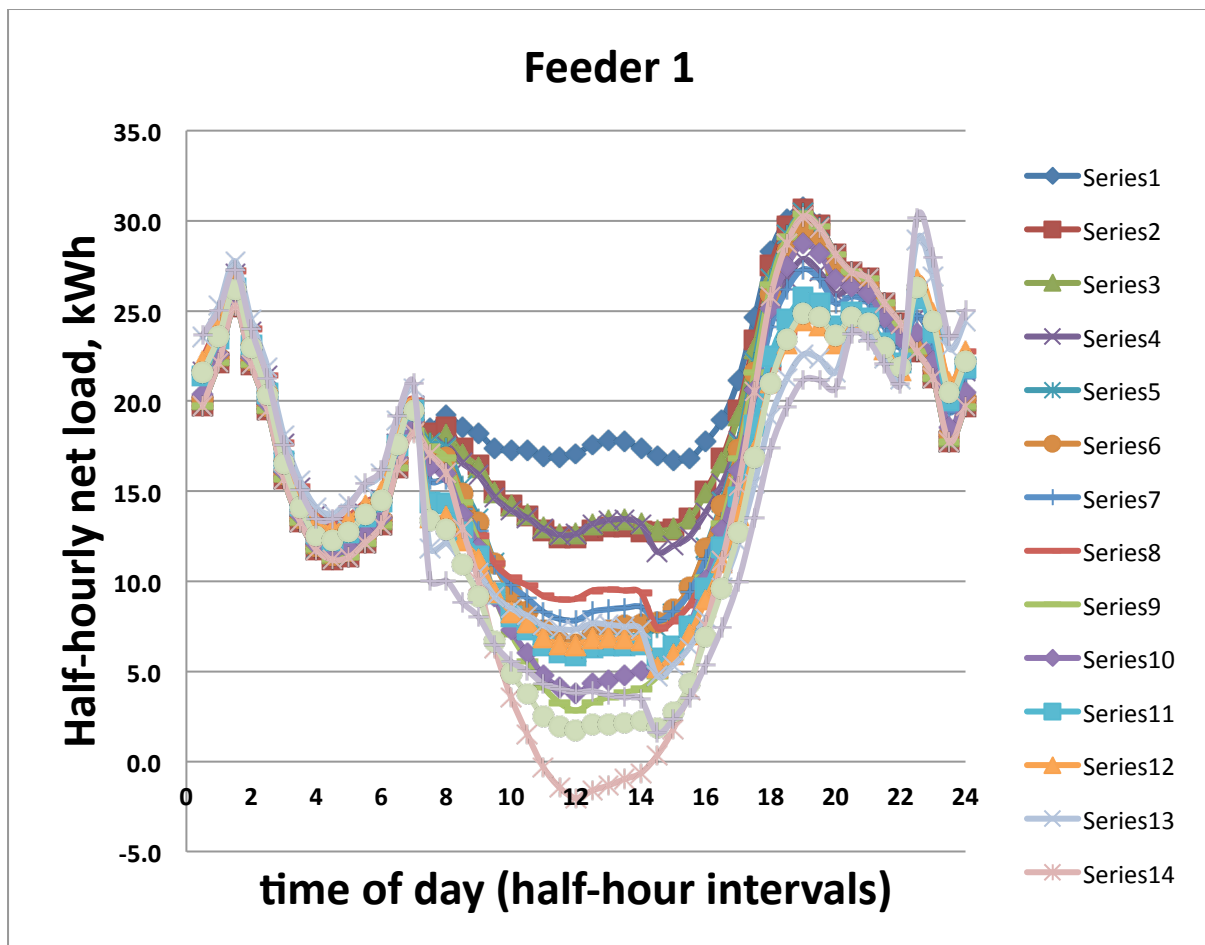


Figure 2-3: Annual average net load of feeder 1 over all 16 scenarios.

The aggregated net load profiles of six feeders (each with 50 homes) over 16 scenarios are illustrated in Figure 2-4. It is evident that as the percentage of homes with PV and battery increases the gap between the scenarios and the base-case scenario (Scenario 1) also increases.

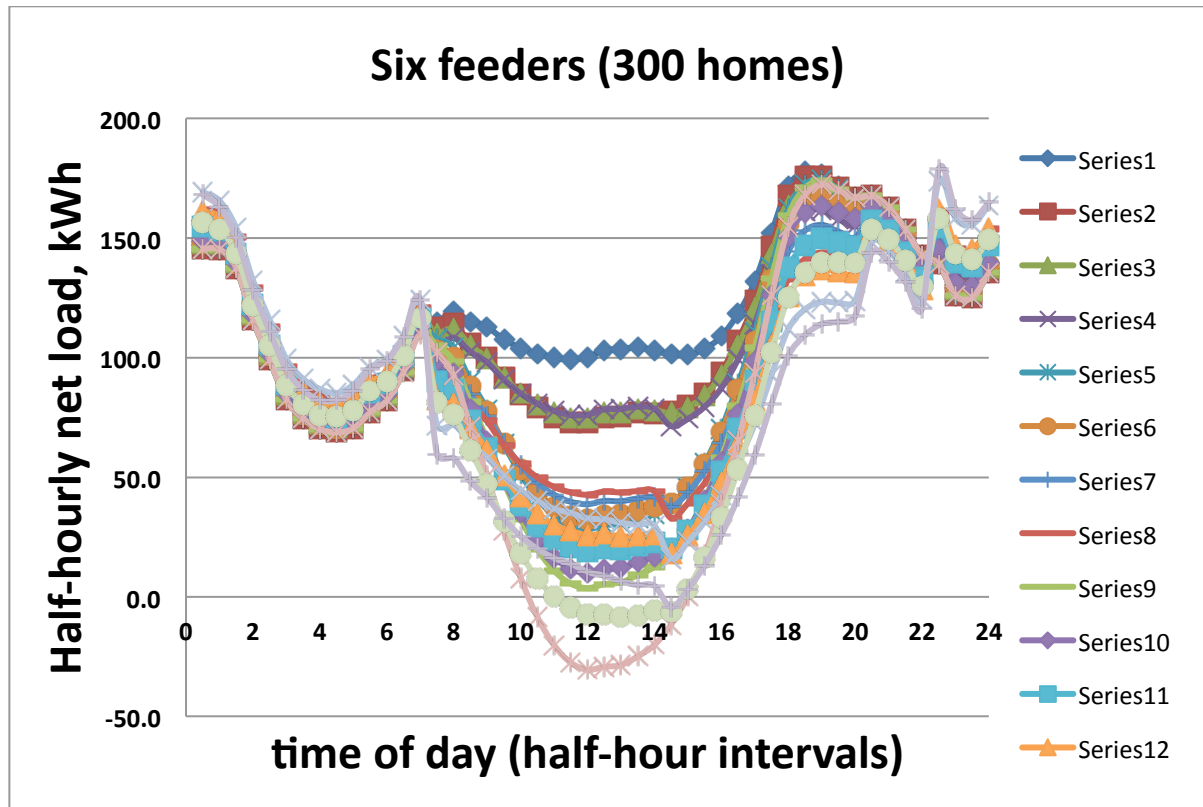


Figure 2-4: Annual average net load of six feeders over 16 scenarios.

An important observation both in Figure 2-3 and Figure 2-4 is the sharp change of the profiles during the periods at which ToU tariffs are changing, i.e. 7 am (from offpeak to shoulder), 2 pm (from shoulder to peak), 8 pm (from peak to shoulder), and 10 pm (from shoulder to offpeak). The sharp decline of net load at 7 am happens to all scenarios with storage. While the net load was relatively high before 7 am due to battery charging, it suddenly drops once the clock hits 7:00 am and the electricity price changes to shoulder ToU tariff. As the solar generation is not yet high, the battery might quickly start discharging and therefore this quick move from charging to discharging mode causes the first steep change in

net load. A very similar steep change happens at 2:00 pm, before which the battery was charging, and suddenly moves to discharging mode as the peak ToU tariff starts. Another disturbance happens at 8:00 pm by which most of the batteries are discharged to maximum DoD and the homes' loads start relying on the grid (in the absence of solar irradiation). The last disturbance happens at 10 pm (start of off-peak) when batteries initiate the charging cycle for the next day.

It is evident from the above discussion that the ToU electricity tariff has a significant impact on the load profile once household storage becomes widely deployed, which enables the end users to shift their load in their personal favour. The ToU pricing, with step function transitions, might not be a suitable tariff structure for future grid operation, as this might result in undesired rapid changes in load profile if consumers respond to such price signals.

2.2 Conclusion

We have scaled up the PV-battery model discussed in Milestone 2 to feeder level. We developed a scenario-based PV-battery study with scenarios spanning from zero percent of PV and battery to 100% of both technologies. We then investigated the net load of a feeder under various scenarios. One of the key findings of this study is that a ToU electricity tariff has a significant impact on demand once storage is widely deployed and enables the end users to shift their load in their personal favour. ToU pricing with a step function between periods might not be a recommended tariff structure for future grid operation as it might promote rapid changes in the load profile if consumers respond sensitively.

Our next step to be reported in Milestone 4 will be the aggregation of feeders to substation level. We will then develop an agent-based model with each substation as one agent. With this we will extrapolate the model to city level.

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3 SECURITY SCANNING TOOLS AND FRAMEWORK

Referring to the Milestone 3 details in Section 1, the modelling framework has been essentially presented in the previous reports. There will be improvements as the research proceeds, but for these early stages the 14-generator Australian NEM model will be used with the added facility to place CSP and wind farms flexibly and to model the demand-side including demand response and storage. Steps are being taken to obtain a more detailed model of the NEM, but there is no guaranteed timing. Hopefully, it will be available for the final stages of the project.

In this Section, we report the progress towards achieving the second milestone point on security scanning tools. The goal of this work is aimed to produce a novel screening tool for the balancing and stability of large numbers of scenarios of renewable power placement. Ultimately, a configuration will only be successful if balancing (in terms of energy, power and ramping) and stability (in terms of angle, frequency and voltage dynamics) meet security specifications.

3.1 Steady-state and dynamic analysis

A power system is usually in steady-state operation or in a state that could with sufficient accuracy be regarded as steady-state (sometimes called quasi-steady-state). A fault such as a short circuit in a power system leads to a dynamic condition. Such an event can start a variety of different dynamic phenomena in the system. So studies with various dynamic models are needed and power system dynamic analysis deals with the power system response to small and large disturbances. This usually relates to dynamics of the system around some equilibrium point (possibly quasi-static). The steady-state analysis of these dynamic equilibria using dynamic power flow models and associated indices can tell us a lot about dynamic behaviour. Thus, in milestone 3, the security scanning tools and framework are based on

steady-state and dynamic analysis. For each scenario considered, the framework can be used to make comprehensive security assessment through diverse scanning tools and finally, the assessment report can be generated. More specifically, the process is illustrated in the following flowchart in Figure 3-1.

The stability analysis of power systems with conventional generation and a large set of possible contingencies in terms of angle, frequency and voltage behaviour became mature in the 1990's – see references [1, 10]. The new challenges created by increasing penetration of renewable power were surveyed in the Milestone 1a Report [11]. The complexity of computation increases considerably to include:

- A large number of scenarios for unplanned DG/RES and its variability with time;
- The more complicated role of the demand-side, including DR and storage;
- The changing inertia profile as RES is dispatched.

The approach we have taken is to set up a comprehensive process for checking stability under all possibilities. Figure 3-1 shows steps from scenario generation through modular analysis and a final statement of stability. Whereas traditional stability analysis approaches stability with separate modelling and analysis for each type, here the approach attempts to integrate these analyses as much as allowed by the state of development of tools. For example, it is possible that a fault near a windfarm can initiate questions about all of angle, frequency and voltage behaviour.

At this stage of the project the software tools assembled include:

- Plexos for market modelling
- DIgSILENT for dynamic analysis, especially with renewables
- PowerTech Tools for some special capability in voltage stability analysis
- MATLAB for research software modules such as for demand-side

These early studies are occurring in parallel with ongoing work on demand-side modelling, so simplifying assumptions are needed.

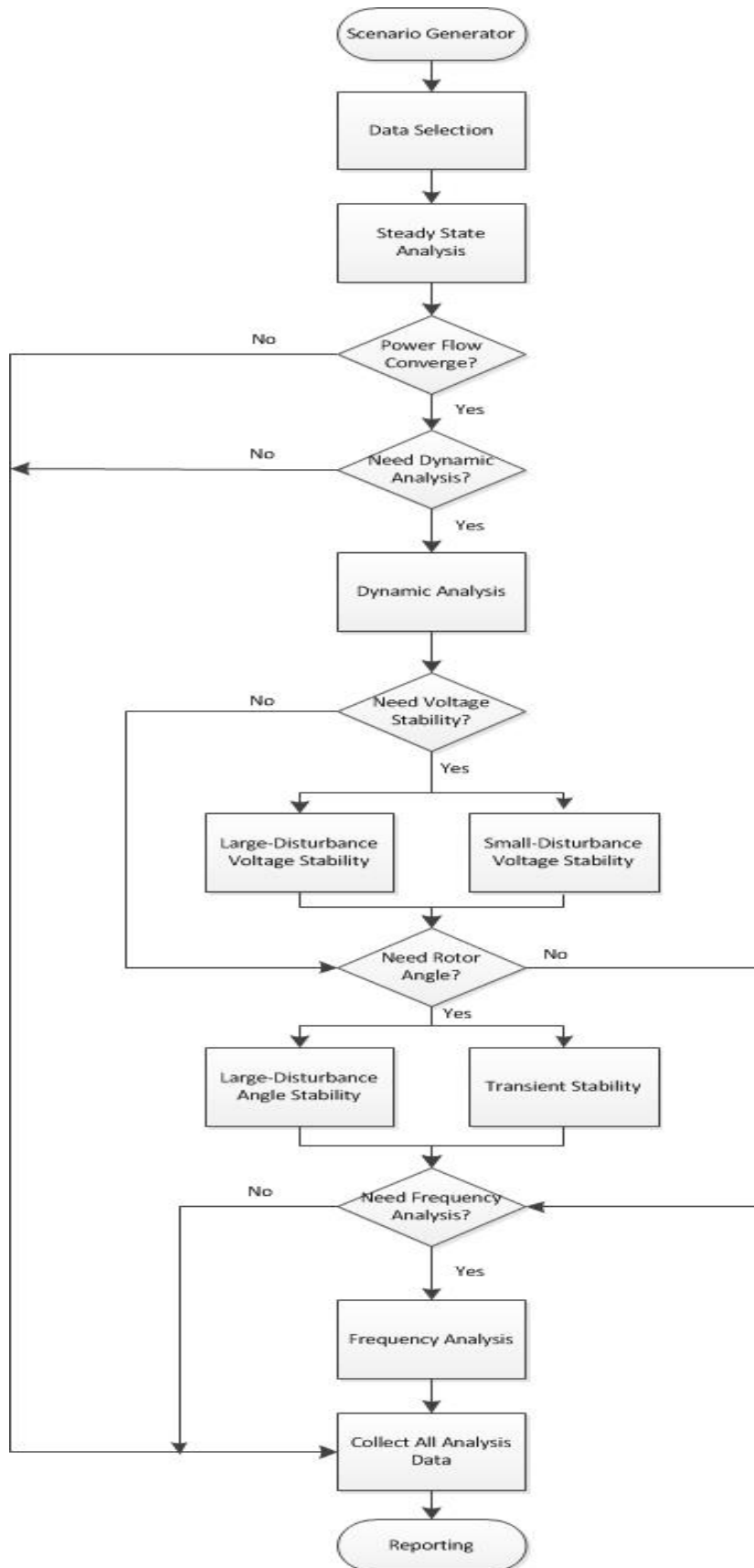


Figure 3-1: Flowchart of security scanning tools and framework

Some comments on the modules are now given.

(1) Scenario Generator

The security scanning tools and framework will be applied to a large number of future grid scenarios. In particular, some typical scenarios suggested by the recent CSIRO Future Grid Forum [12], Zero Carbon Australia Report [13] and the AEMO 100% Renewables report [14] will be effectively analyzed. These include the following:

(a) Rise of the Prosumers

Prosumers are the residential customers who also supply their own electricity. The sustained high retail prices of electricity, falling costs of solar roof-top panels and increasingly innovative financing and product packaging from energy services companies leads to large increases in the scale of on-site generations. This can be modeled by aggregate demand-side modeling as described in Milestone Report 1b [15]. Parameters in this model can capture the percentages of uptake for the technologies involved. Improvements to this model are expected from Part B of project 1.

(b) Power Grid with 100% Industry Load (or Leaving the Grid)

As the number of prosumers increases, an extreme situation arises where in future, the customer load may be off grid, i.e. customers will generate, trade, consume, and store electricity for themselves. Thus, the loads connected to the power grid will be mainly industry load. We will consider an extreme scenario where all loads connected to the transmission grid are industry load.

(c) Renewables booming

It is well known that Australia has an abundance of renewable energy resources, such as wind, solar, geothermal etc. While current Government steps are not encouraging the possibilities here on any scale, it is easy to imagine a scenario where a Government of the near future does drive Australia to developments comparable to those in California and parts of Europe. We will form scenarios that represent the increasing to high usage of renewable energy sources.

(d) 100% renewables in Australia

The Zero Carbon Australia 2020 plan more specifically suggests that 100% RES is possible by 2020. Similarly, the UNSW team in our cluster also produced simulations of scenarios with 100% renewable energy for the National Electricity Market (NEM). They concluded that it is technologically feasible within the specified NEM reliability standard. These studies are proposals in the sense that complete studies of security have not yet been carried out (beyond basic balancing). Through comprehensive analysis, we will aim to show how 100% renewables scenarios would affect the future grid performance.

(2) Steady State Analysis

The primary analysis tool for steady-state operation is power flow analysis, where the voltages (magnitude and phase), line power flows and losses in the system are determined. This analysis is widely used for both operation and planning studies throughout the system i.e. both transmission and distribution systems. A number of software implementations can be applied for steady-state analysis; we use the DIGSILENT Version 15.0 in the proposed framework because of its flexibility with modeling renewable power. Specifically, the power flow calculation is based on the Newton–Raphson method, which gives a fast convergence.

In studying balancing with faster ramping situations, we need to assume that the RES variations are slower than the relevant system dynamics in order to use (quasi-static) power flow. The situation where this does not hold is also under investigation in an associated PhD project on sensitivity of dynamics to renewable power type, scale and placement in test systems and the NEM.

(3) Dynamic analysis

Power system dynamic analysis aims to analyze the ability of an electric power system to regain a state of operating equilibrium after a physical disturbance for a given initial operating condition [1, 10]. The basic security requirement after balancing (energy, power

and ramping) is maintaining adequate stability margins (angle, voltage, frequency) for specified contingencies. Power system stability for classical grids can be divided into three types [11], i.e. voltage stability, (rotor) angle stability, frequency stability.

(3.1) Voltage Stability Analysis

Voltage stability analysis can be classified as large disturbance voltage stability and small disturbance voltage stability. In the following section, we will briefly introduce how to assess these two categories of voltage stability.

(a) Large Disturbance Voltage Stability

Large disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. Determination of large-disturbance voltage stability requires the examination of the nonlinear response of the power system over a period of time sufficient to capture the performance. The study period of interest may extend from a few seconds to tens of minutes.

For example, in this study, we can choose a large disturbance defined as follows: The event consists of a single phase short circuit to ground at time point 0 and is cleared after 0.1s at the connecting transmission line between NSW and QLD, namely from node 205 to node 416. After the large disturbance event, we use the DIGSILENT to depict voltages on any selected buses, including magnitude or phases to see the dynamic performances of the system.

(b) Small Disturbance Voltage Stability

Small disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls. With appropriate assumptions, system equations can be linearized for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors

influencing stability. In this study, we choose the small disturbance defined as: the event consists of a load decrease disturbance occurs at time point 0 of node 207 in NSW. It decreases insignificantly in terms of the active/reactive power. Besides, we can also choose some other types of small disturbance to test the capability of system to maintain voltage stable, such as to increase the load, etc. Then, similarly with the large voltage stability analysis, we can also use DIgSILENT to simulate the dynamic performance for testing the system. Tracing eigenvalues as parameters change is also useful. For this, PowerTech Tools can be used. The voltage magnitude and the angles can be recorded in the final report part.

(3.2) Rotor Angle Stability

Rotor angle stability refers to the ability of the synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. In the scanning tools, similarly with voltage stability, we can run two different analysis processes to fit the needs.

a. Small-disturbance Stability

In this part, we still use DIgSILENT and/or eigenvalue solvers to implement the process for assessing the ability of the grid to maintain synchronism and stable damping under small disturbances.

b. Large-disturbance Stability

Large-disturbances may involve large excursions of generator rotor angles which are influenced by the nonlinear power-angle relationship. The DIgSILENT analysis tool features rotor angle analysis of a dynamic multi-machine system. It covers all network components such as generators, motors, loads, SVS, FACTS, or any other component used in the system representation, including controllers and power plant models.

It is also useful to consider tools such as the so-called Extended Equal Area Criterion, which is implemented in PowerTech Tools and can give margins of stability for a wide range of contingencies and scenarios.

3.3 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability occurs in the form of sustained frequency swings leading to the tripping of generating units and/or loads.

Again DIgSILENT is appropriate for frequency oscillatory stability studies. The analysis is a natural complement to the time domain simulation environment. It also allows for the computation of modal sensitivities with respect to generator or power plant controllers, load characteristics, reactive compensation or any other dynamically-modelled equipment.

3.2 Initial analysis results

3.2.1. Static Analysis

First, we divide daily the load curve into three different levels, i.e. light load level (0 am-8 am, 22 pm-0 pm), medium load level (9 am-17 pm) and heavy load level (18 pm-21 pm) respectively. In each scenario, the penetration of the wind farm and photovoltaic maintains 6.46%. In different time points in a day, the power outputs of the wind farms and PV stations are drawn from the real-time data of AEMO online reports. From the practical power output data, we can convert the corresponding capacity factor of the different types of generators throughout the day. The power flow of the 180 lines in the system with 6.46% renewable penetration level in a day can be illustrated as follows.

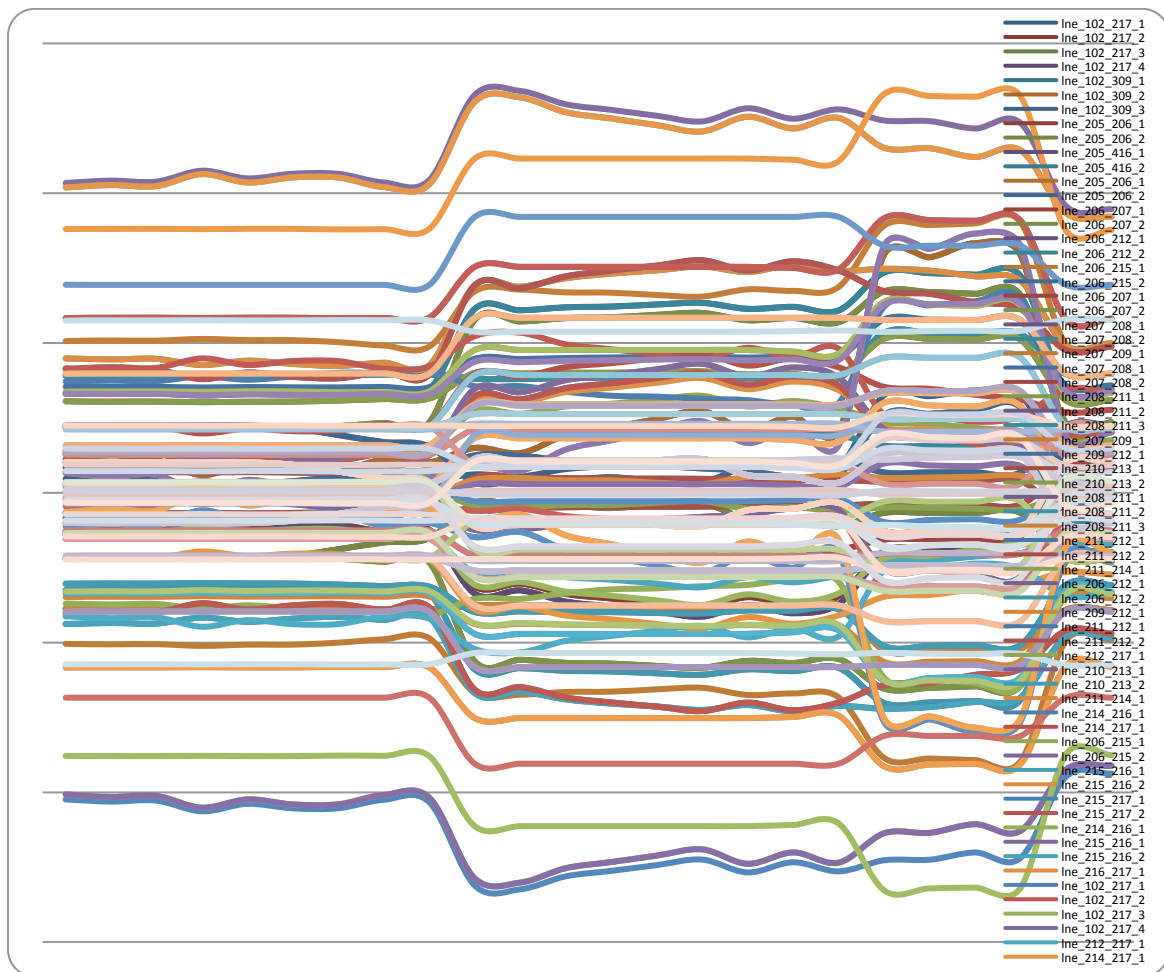


Figure 3-2: Power flow of the 180 lines in the system with 6.46% renewable penetration level

Generally, based on different scenarios, we can achieve different static analysis results and the violations, if existing, can be identified.

3.2.2. Dynamic Analysis

As Figure 3-1 illustrated, we can divide the dynamic scenarios into three sub-categories, i.e. rotor angle stability, frequency stability and voltage stability, and small disturbance and large disturbance analysis are involved in two of them. The following five figures of the simulations demonstrate the selected specific scanning tools. In order to test the impacts of the renewable energy sources, we integrate the PV power station in QLD while wind farms in NSW, SA and VIC. Similar with the power flow calculation, the penetration level of renewable sources is 6.46%.

The large disturbance is as previously defined as:

- ✓ The event of single phase ground short circuit happens at time point 0 and is cleared after 0.1s between the connecting transmission line between NSW and QLD, namely on the line from node 205 to node 416.

The small disturbance is also as defined:

- ✓ The event of load decrease disturbance occurs at time point 0 of node 207 in NSW. It decreases 5% of the active/reactive power, namely 94MW.

The following figures show the dynamic performances of voltage, frequency and rotor angle in different processes (We choose the voltage and frequency of node 205 & 416 near the short circuit point and the node 302 away from the point. The rotor angles are from a nearer generator 201 and a farther one 302).

2.1 Rotor Angle

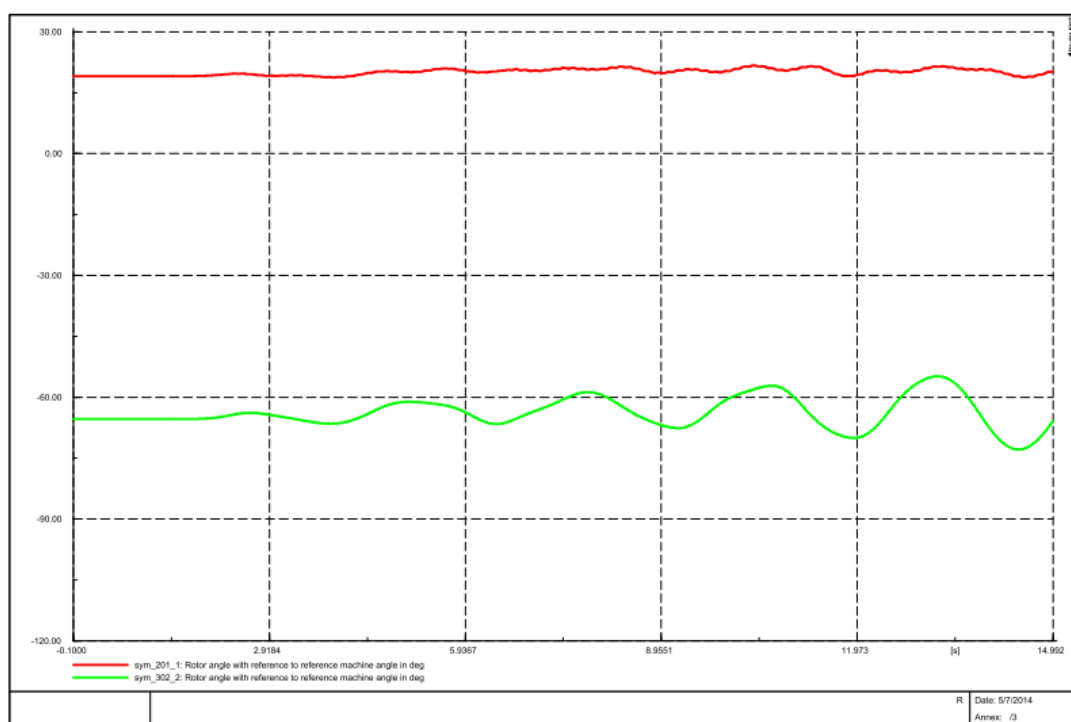


Figure 3-3: Small Disturbance Stability of Rotor Angle

2.2 Rotor Angle

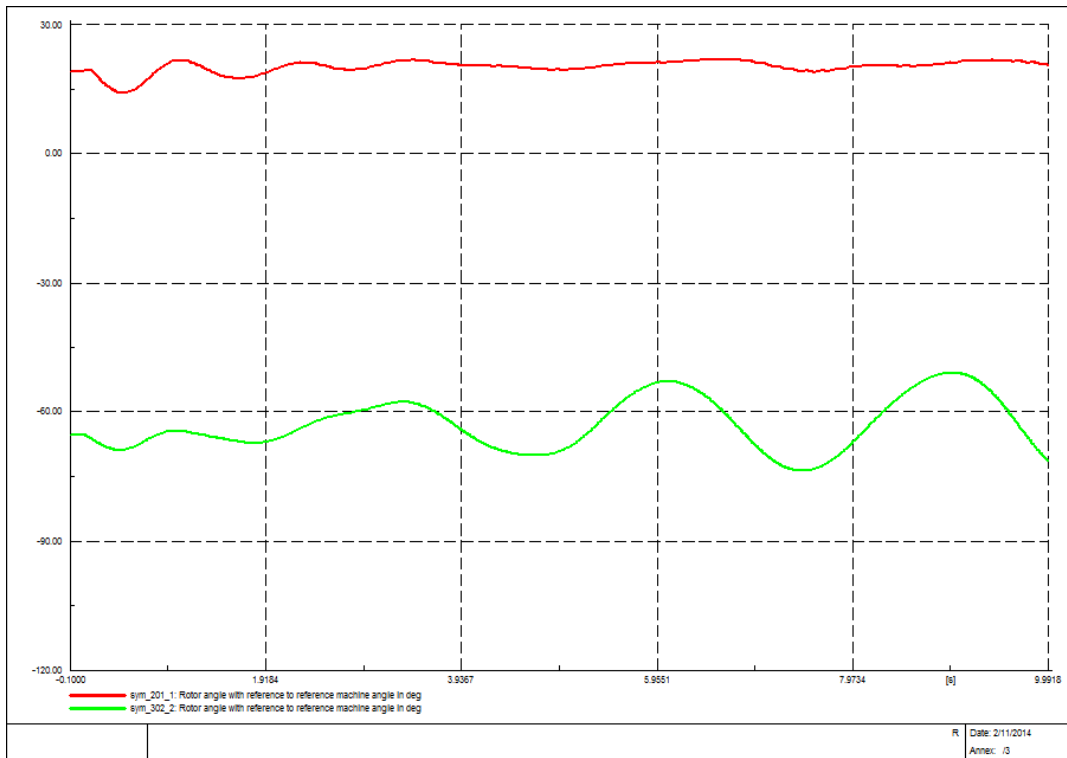


Figure 3-4: Large Disturbance Stability of Rotor Angle

2.3 Frequency Stability

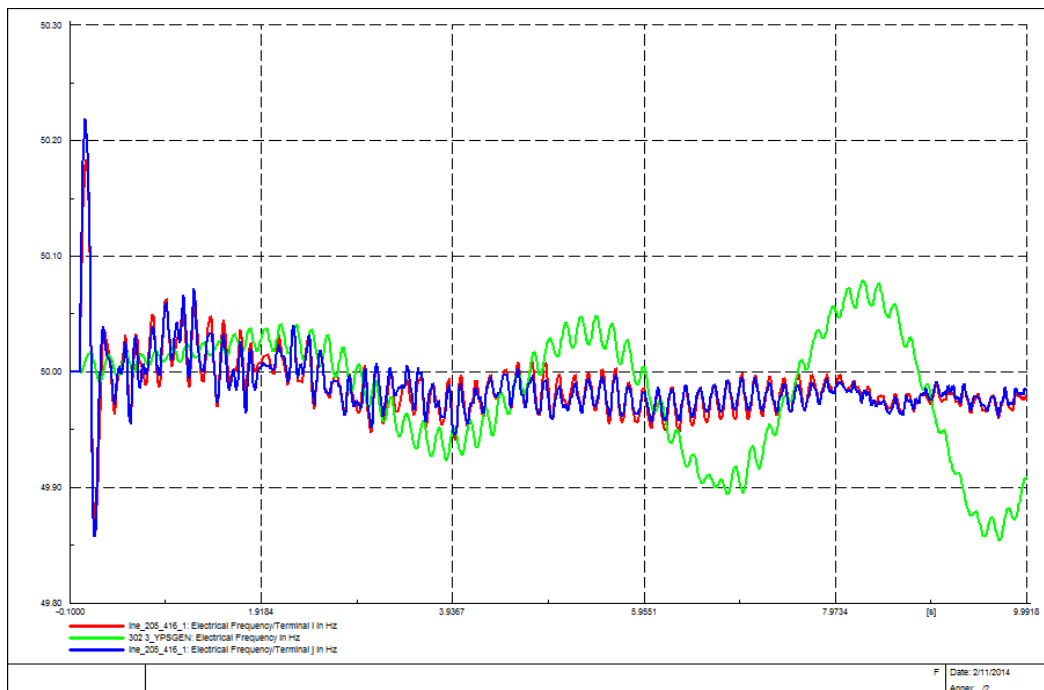


Figure 3-5: Frequency Stability

2.4 Voltage

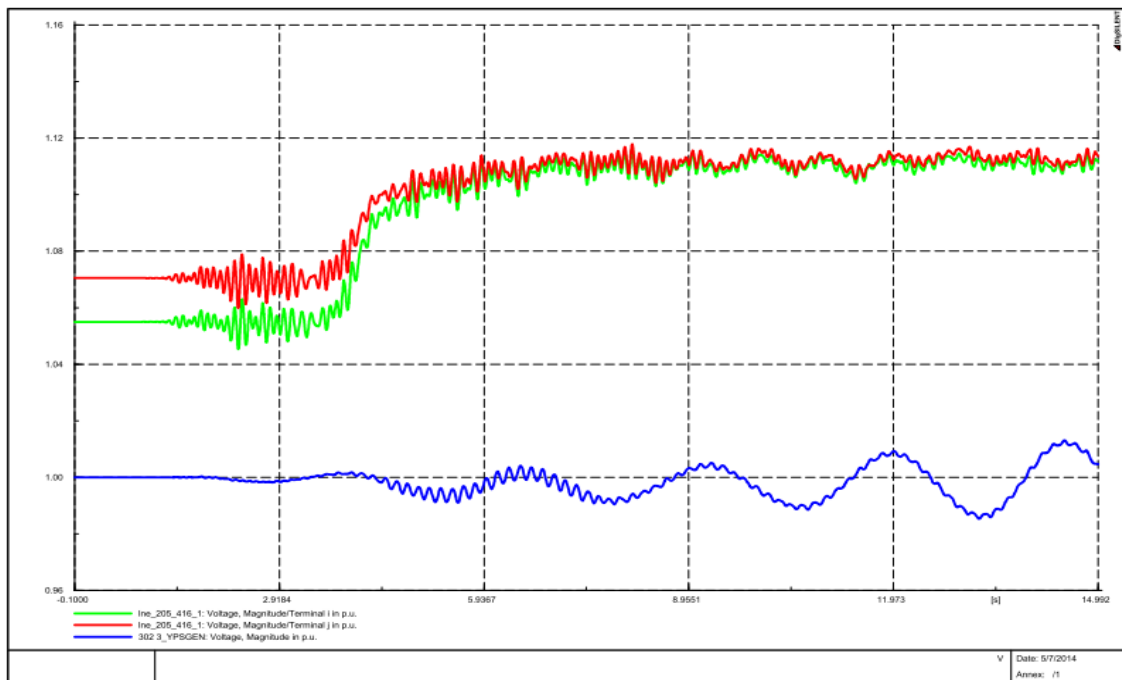


Figure 3-6: Small Disturbance Stability of Voltage

2.5 Voltage

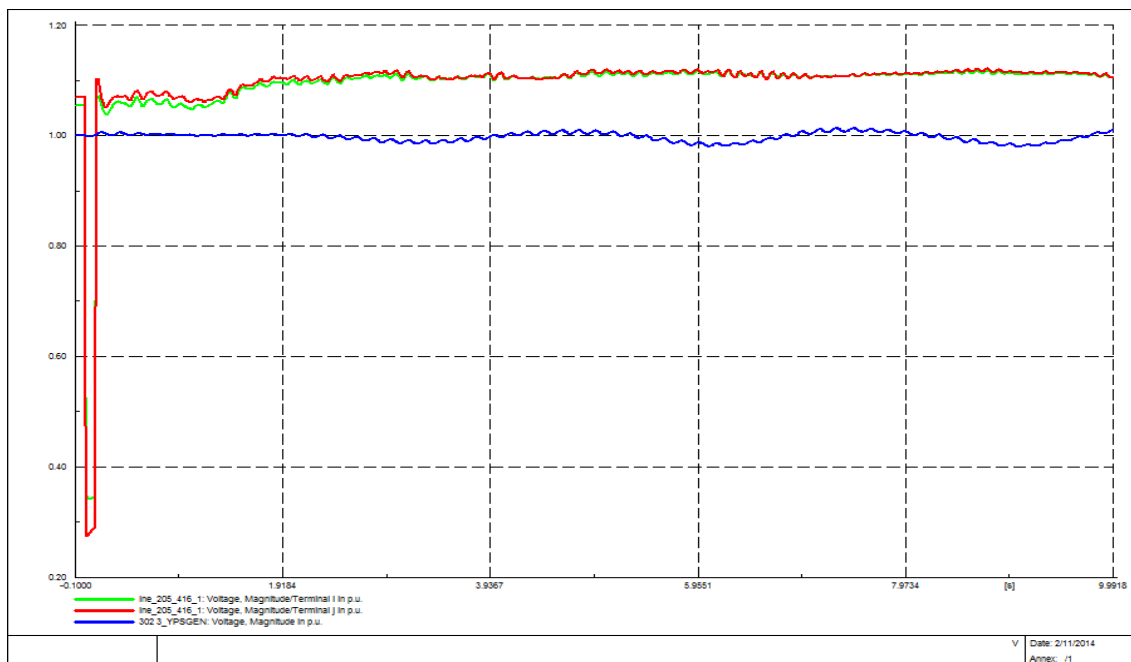


Figure 3-7: Large Disturbance Stability of Voltage

These curves just illustrate the capability of the analysis package. The current work is exploring how to use this to scan scenarios of RES placement for situations which facilitate balancing and stability.

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4 MID-TERM PROGRESS REPORT

As explained in previous reports and above, this Project 1 fell naturally into two parts led by Professors Vassallo (modeling storage) and Hill (modeling dynamics and security) respectively. Storage has a key role in long-term scenarios because of its potential as a 'game-changer', i.e. inexpensive storage at household and/or grid level can totally change the previous limitations on power networks. Modeling large grid-connected storage is not difficult, but modeling the effect of distributed storage in combination with DG and mechanisms for DR is another matter. The approach we have taken is to assume that

consumers always behave to optimize, whether it is to install a resource for generation and/or storage or to operate a given facility. The Future Grid Forum used highly aggregated models at state level for the NEM. At this stage we have got to model aggregations at feeder level using real data and more speculatively at city level. The progress to be made has to include:

- Extension of the data-based models to validation at city level;
- Extension of these models to include customer choices that include use of gas.

This last point is a recent concern in view of further uncertainty for consumers and creates a second level of interaction between electricity and gas networks, i.e. to the co-planning being considered in Project 2. Scenarios from Project 4 to do with gas prices will need to be integrated.

For modeling dynamics, the framework for analyzing scenario/contingency analysis has been established. The progress that must occur now includes:

- More complete scanning of scenarios with attention to issues at interstate connectors for the NEM;
- A process for the stability limits here to inform the optimizations in Project 2 (being studied now);
- Use of the better demand-side models as they arise (from Project 1B);
- Much more extensive case studies, hopefully with a more complete NEM model.